

Control of Naval Electric Drives
Status Report
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Overview

- **Tasks**
- **Task Status Review**
- **Planned Activities**

Tasks: General

Long range goal: develop control tools that are enabled by, and which fully utilize the capabilities of new switches (PEBB hardware).

Sharp control design and analysis tools are to be developed as yardsticks for practical design. Those include:

- energy-flow based, dissipative nonlinear controllers,
- robust controllers that tolerate realistic uncertainties,
- global controllers that achieve global exponential stability.

Tasks: Specific

- Dissipative (Lagrangian) control of permanent magnet machines (PMSM):
 - feedback enhancing both dissipative components and lossless flow between the electrical and mechanical subsystems.
 - adaptation,
 - operation without mechanical sensors (“sensorless”)
- Re-examination of the electric drive control structure - quantifying the suboptimality of nested control loops (current - speed - position),
- Torque ripple minimization in switched (variable) reluctance motors (SRM),
- Experimental verification for DC motors, SRM and PMSM.

Task update

- Permanent Magnet Motor:
 1. Encouraging results in analysis and simulation
 2. Preliminary experiments.
- Servo controller structure:
 1. New results in analysis and design,
 2. Experiments.
- Switched reluctance motor:
 1. New experimental results,
 2. New inverter tested, new motor being installed.

Permanent Magnet Drives: Passivity in a nonlinear system

Standard d-q model of a permanent magnet synchronous motor:

$$\begin{aligned}L_d \frac{d}{dt} i_d &= \omega L_q i_q - R i_d + v_d \\L_q \frac{d}{dt} i_q &= -\omega L_d i_d - R i_q - \omega M I + v_q, \\J \frac{d}{dt} \omega &= M I i_q - (L_q - L_d) i_d i_q - B \omega - T_L\end{aligned}$$

A Lagrangian model form with a normalized state vector:

$$\dot{x} = -(\mathcal{C}(x) + \mathcal{R})x + \mathcal{B}u + \mathcal{F}T_L$$

where $x = [\sqrt{L_d} i_d \quad \sqrt{L_q} i_q \quad \sqrt{J} \omega]$

Controller Design: an Outline

1. The closed loop coupling between the electrical and the mechanical subsystems is increased by adding the transient component to the desired motor torque:

$$T_{M,d}(t) = T_{M,\infty} + \sigma\sqrt{J}e_d(t)$$

where the steady state motor torque is $T_{M,\infty} = \dot{\omega}_d + B\omega_d + T_L$.

2. Voltage $u_d = [u_{1,d}, u_{2,d}]^T = [v_{d,d}, v_{q,d}]^T$ is selected to balance the differential equations of the electrical subsystem with the desired currents.

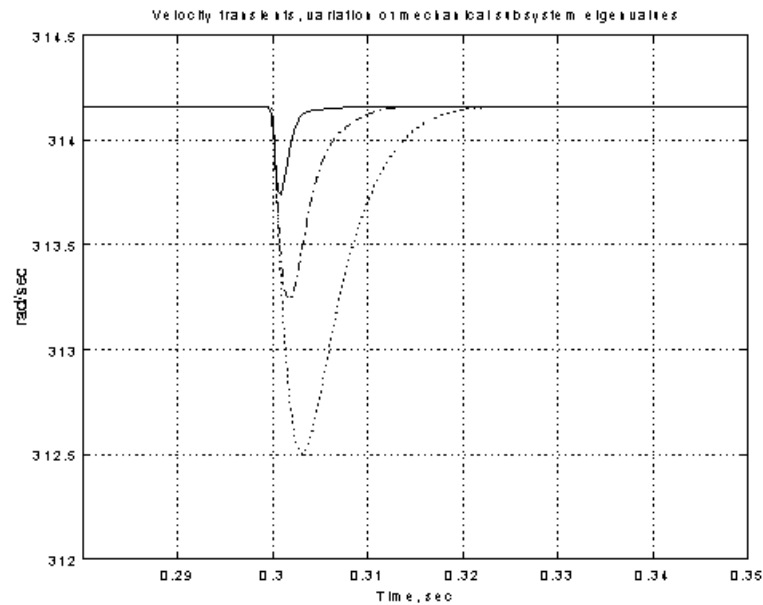
3. Incremental state $e = x - x_d$ represents the transient difference between the actual and desired states.

4. A second input voltage component u_e is designed to assure global stability of the origin in the dynamics of e .

5. The applied voltage is $u = u_d + u_e$.

Simulation Results

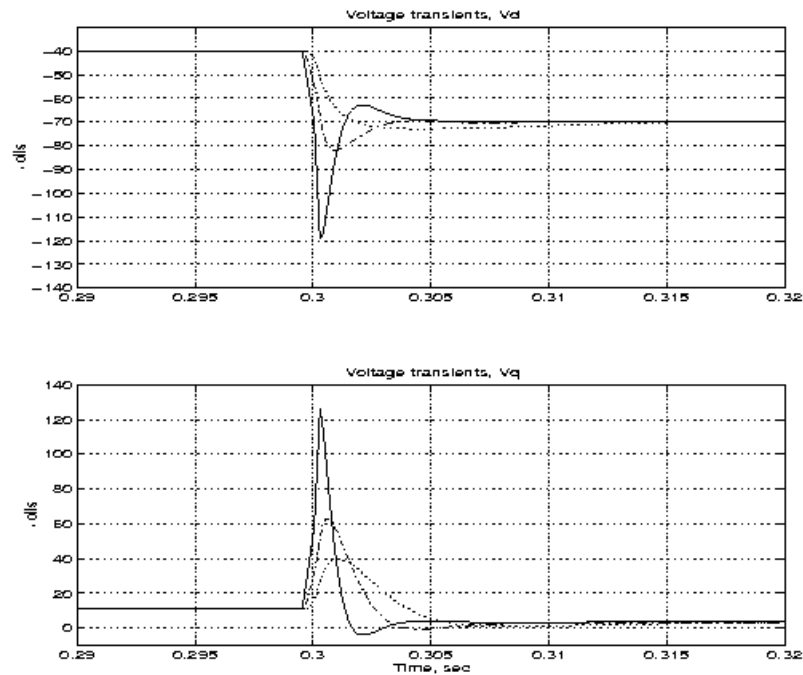
The PMSM: 2 hp, 314 rad/sec.



Velocity transients for variation of mechanical subsystem eigenvalues placement.
Step change in the load torque to 100% of its rated value.

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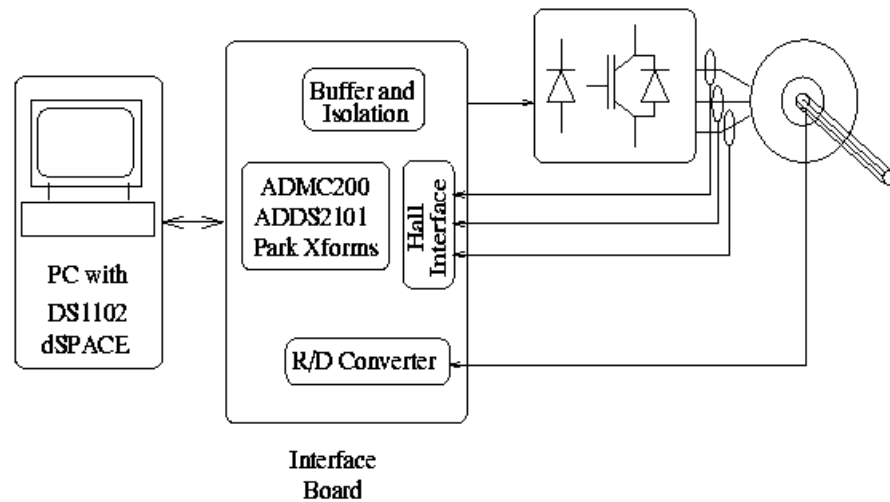
Simulation Results



Commanded voltage transients for variation of mechanical subsystem eigenvalues placement. Step change in the load torque to 100% of its rated value.

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Permanent Magnet Drives, cont. 1

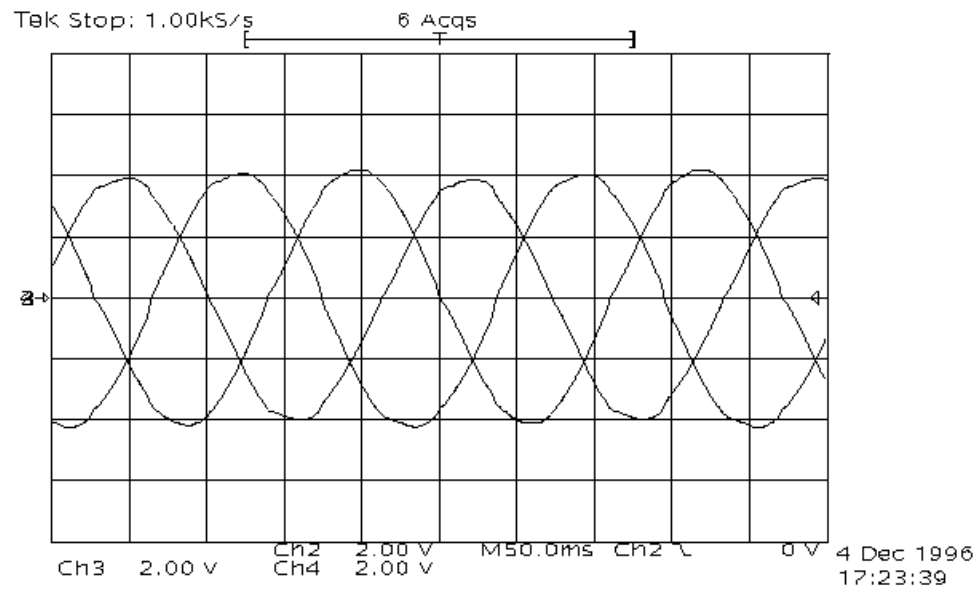


Block diagram of the experimental setup.

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Permanent Magnet Drives, cont. 2

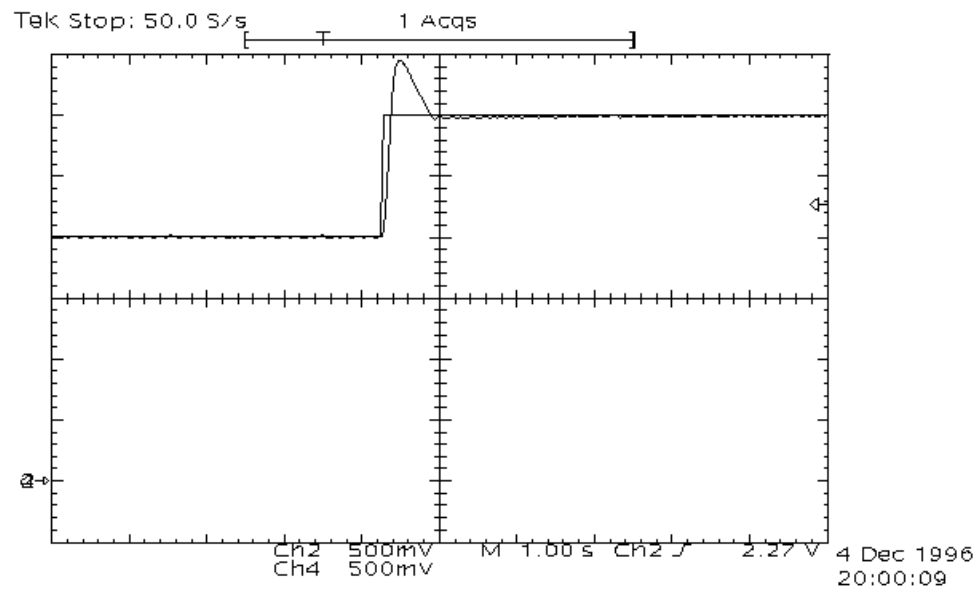
Experimental results - steady-state currents



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Permanent Magnet Drives, cont. 3

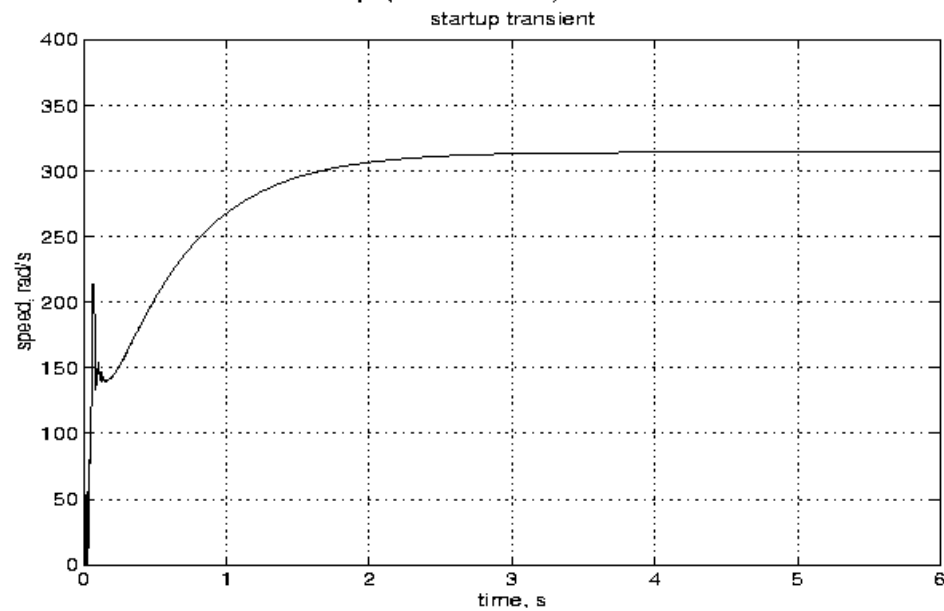
Experimental results - speed transient (PI controller)



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Permanent Magnet Drives, cont. 4

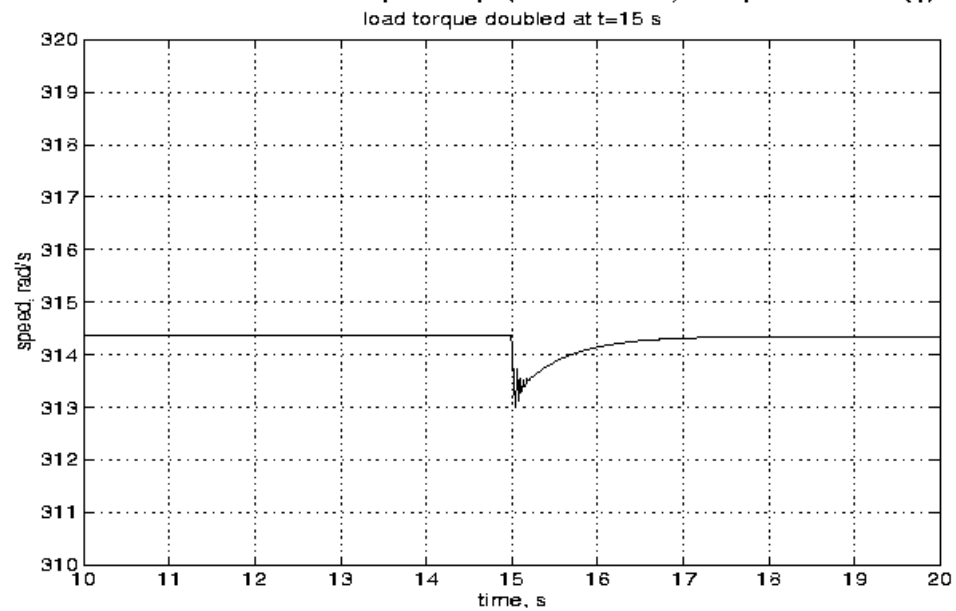
Parameter estimation - start-up (simulation; initial estimates 100 % off).



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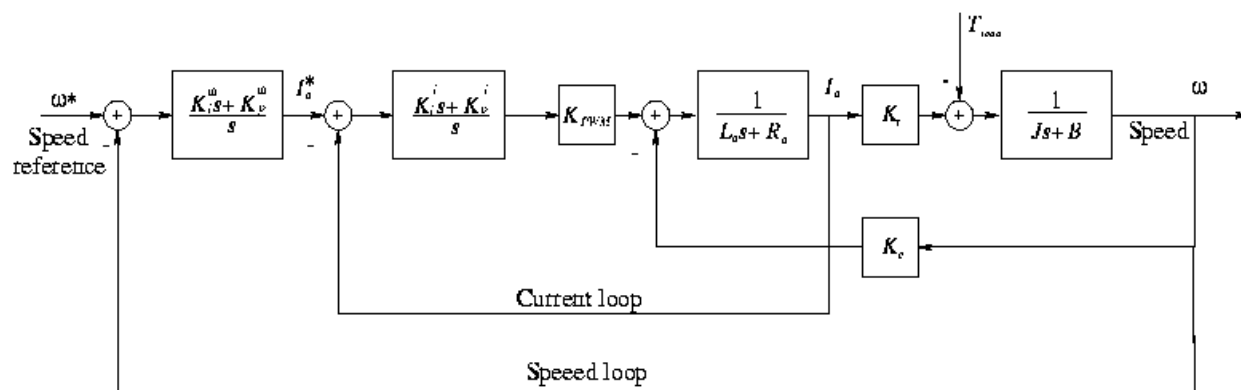
Permanent Magnet Drives, cont. 5

Parameter estimation - load torque step (simulation; torque doubling)



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Control Structure for Electric Drives



Conventional control structure of a (DC) speed servo drive.

Control Structure for Electric Drives, cont. 1

Exploring the suboptimality of the nested loop structure:

- Limits of performance using linear operator-theoretic tools (μ , DC motor example),
- Dissipativity-based tools - considering the mechanical subsystem as a passive perturbation.

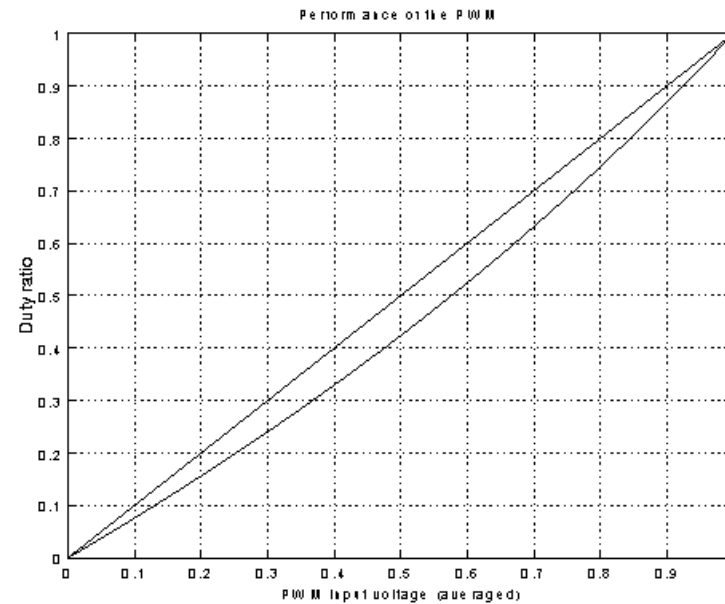
Models for the (nonlinear) Pulse Width Modulation (PWM) and actuator saturation are critical.

Control Structure for Electric Drives, cont. 2

- Based on classical averaging theory,
- Analysis tool - assumes (simple) speed/current controllers,
- Calculates effects of finite switching frequency on PWM gain reduction (up to 20 % in our example),
- Very effective for current ripple calculations.

Control Structure for Electric Drives, cont. 3

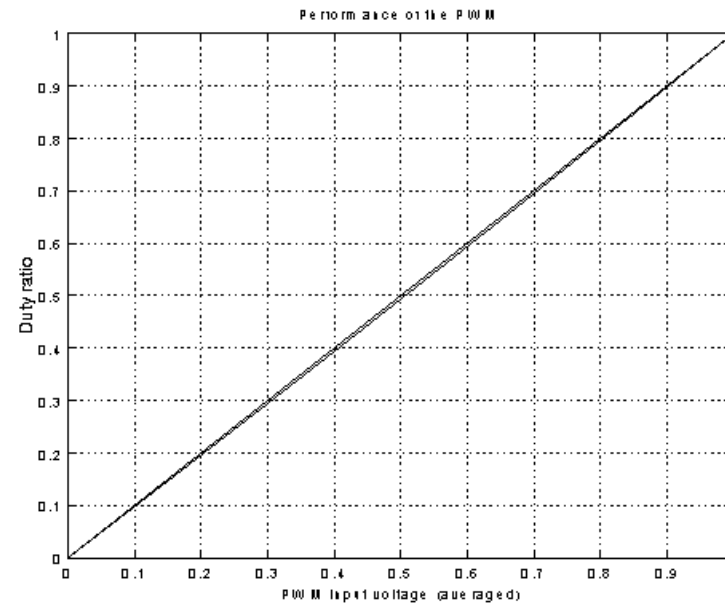
Switching frequency 1.5 kHz.



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Control Structure for Electric Drives, cont. 3

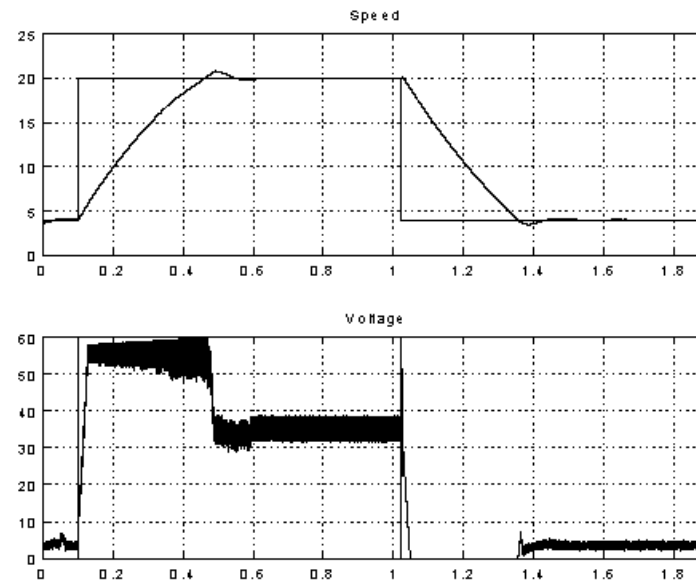
Switching frequency 15 kHz.



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Control Structure for Electric Drives, cont. 4

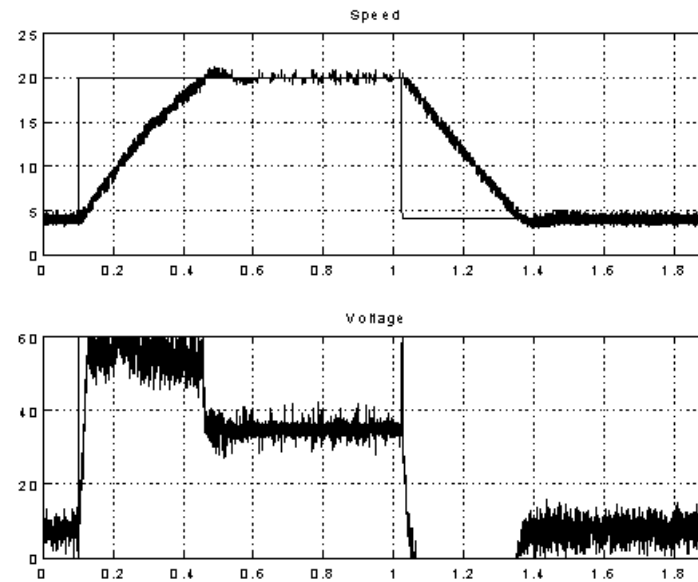
DC motor speed transients - PI controller (simulated).



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Control Structure for Electric Drives, cont. 5

DC motor speed transients - PI controller (experiment).



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Control Structure for Electric Drives, cont. 6

- Voltage magnitude limitations (200 V in our example) constrain the achievable closed loop bandwidth.
- In the example this “effective bandwidth” is approximately two decades below the switching frequency.

Switched Reluctance Motor (SRM) Drives

Main characteristics:

- robust, brushless construction,
- fault tolerant,
- nonlinear magnetics,
- hard to control:
 1. torque ripple,
 2. acoustic noise (doubly salient).

Strategies for reducing ripple often ask for:

- substantial actuation effort,
- (vanishingly) small model uncertainty.

SRM Drives, cont. 1

Optimization criteria for currents:

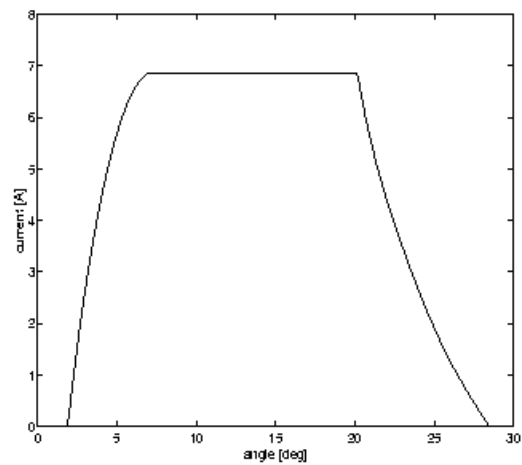
- Minimization of the highest voltage required over a cycle

$$\min_{i(\theta)} \{ \max_{\theta} \{ |v(\theta)| \} \} | T_0$$

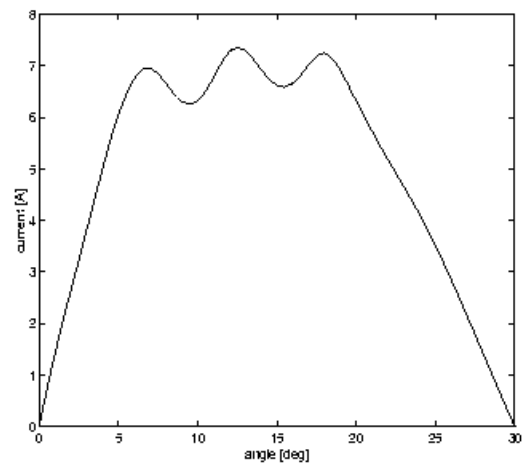
- Maximization of the achievable ripple-free torque in high-speed,
- Maximization of efficiency,
- Minimization of ripple in radial forces.

SRM Drives, cont. 2

Constant current waveform



Optimal current waveform



SRM Drives, cont. 3

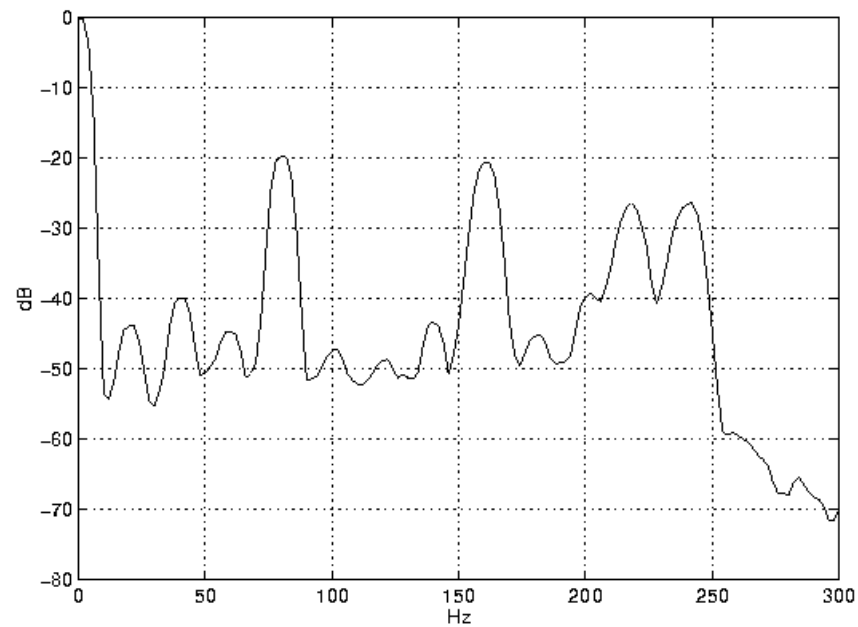


Figure 1: Measured magnitude spectrum of the torque ripple, conventional switching policy

SRM Drives, cont. 4

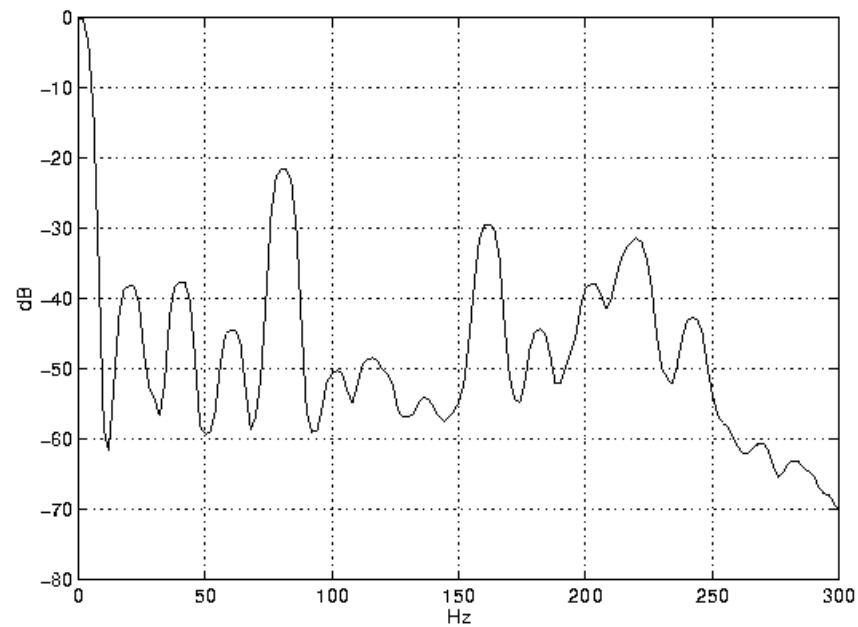


Figure 2: Measured magnitude spectrum of the torque ripple, optimized switching policy, hard chopping

SRM Drives, cont. 5

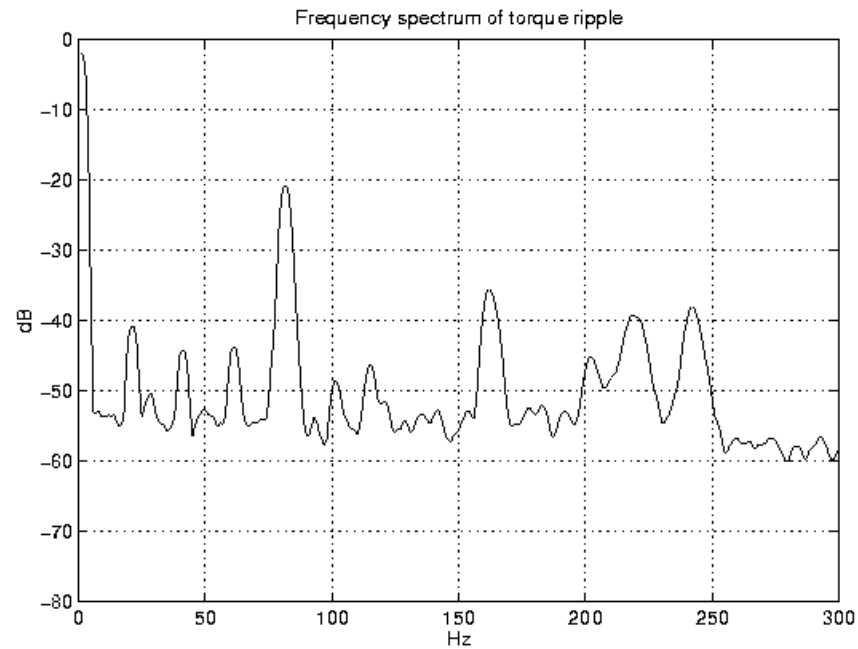


Figure 3: Measured magnitude spectrum of the torque ripple, optimized switching policy, soft chopping

Planned Activities

- permanent magnet drive:
 1. refinements of the test bed,
- adaptation in dissipativity-based control.
- modeling of saturation of PWM converters in drive applications (theory and experiment),
- switched reluctance drive:
 1. shaft-sensorless operation,

Analytical background: Dissipativity

$x(t) \in \mathbb{R}^n$ (state)

$u(t) \in \mathbb{R}^m$ (input)

$y(t) \in \mathbb{R}^p$ (output)

$V : \mathbb{R}^n \rightarrow \mathbb{R}_+$ storage function

$s(u, y)$ supply rate (often quadratic)

Dissipativity: For any $t_0 \leq t_1$

$$V(x(t_0)) + \int_{t_0}^{t_1} s(u, y)(t) dt \geq V(x(t_1))$$

$$s(u, y) = \|u\|_2^2 - \alpha^2 \|y\|_2^2, \quad \alpha \geq 1 \quad \text{Attenuation}$$

$$s(u, y) = u^T y \quad \text{Passivity}$$

Analytical background, cont. 1

Theorem A (feedback) interconnection of dissipative systems (+ some technical conditions) is stable (in a suitably chosen sense).

Large scale system extensions (Vidysagar 1980).

This property complements (and sometimes replaces) the more stringent *linearity* requirement.

A variety of powerful **computational methods** is available.

SRM Drives, cont. 3

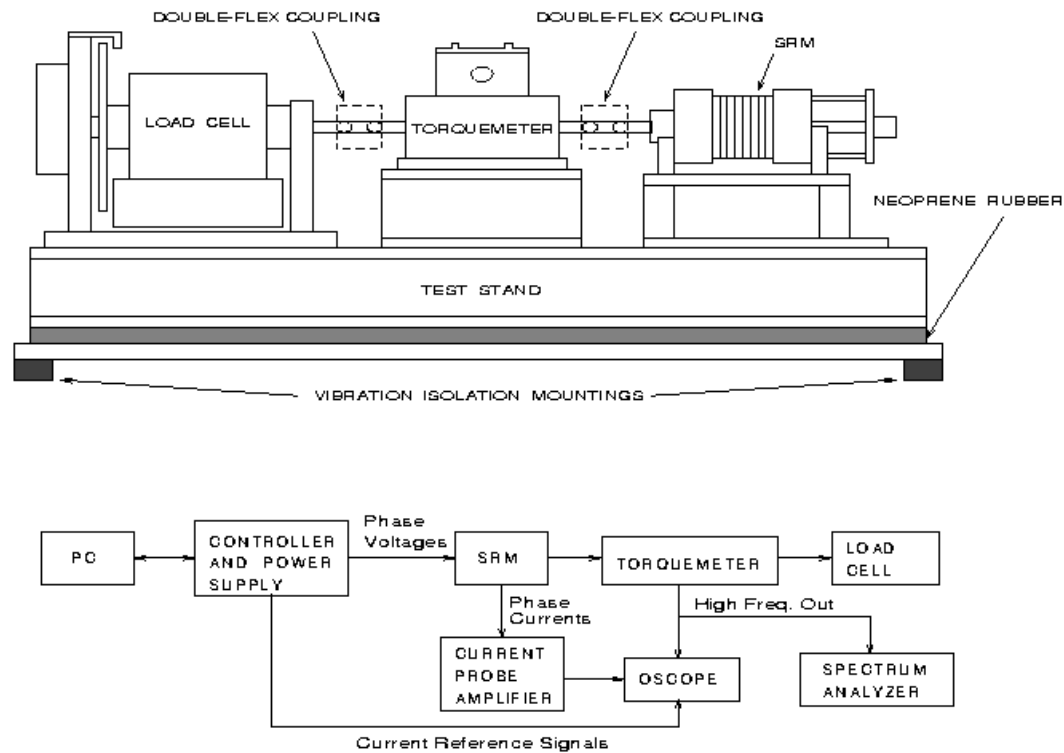
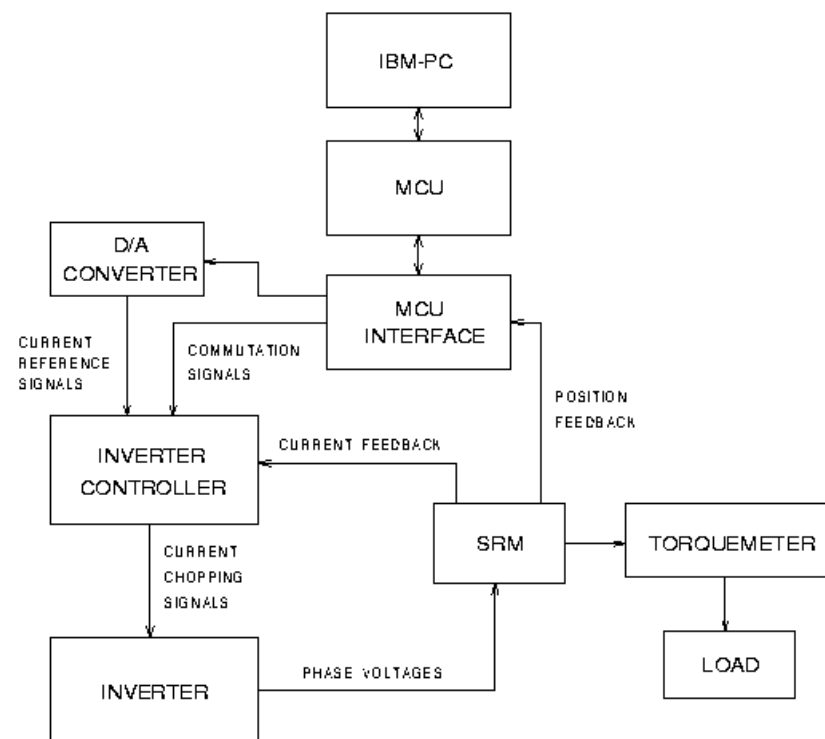


Figure 4: Experimental test-stand
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SRM Drives, cont. 4



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SRM Drives, cont. 5

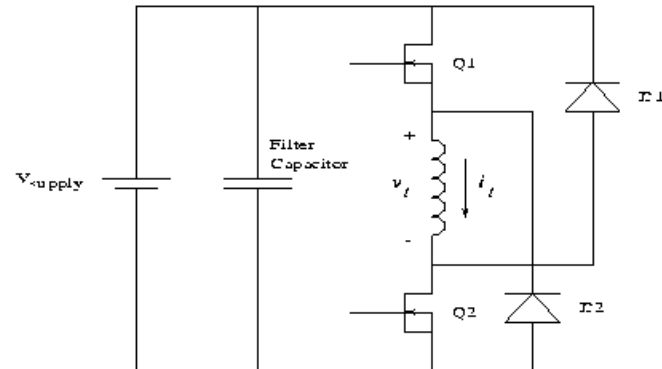


Figure 5: Soft Chopping

Switching modes:

- $Q1$ and $Q2$ ON: $V_{load} = V_{supply}$;
- $Q1$ OFF, $Q2$ ON: $V_{load} = 0$;
- $Q1$ and $Q2$ OFF: $V_{load} = -V_{supply}$.